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THE EFFECTS OF SURFACE DISTURBANCE ON VEGETATION IN THE NORTHERN CANADIAN ARCTIC ARCHIPELAGO

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "The Effects of Surface Disturbance, on Vegetation in the Northern Canadian Arctic Archipelago" submitted by Thomas Alan Babb in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

A combination of surface manipulation experiments on Devon Island, N.W.T. and extensive investigations of disturbance on other High Arctic islands was undertaken. These provided information in a variety of habitats on the physical and biological effects of removal of vegetation by blading or vehicle movement, spillage of diesel fuel, animal grazing, and fertilization.

Surface energy relations on artificially bladed and control plots on Devon were determined, and thaw depth and soil temperature profiles at disturbed sites on other islands were measured. Results indicate that although albedo decreases, soil heat flux and subsequent thaw are affected relatively little by removal of vegetation. This is partly due to lower air and permafrost temperatures than in the Low Arctic, and therefore to higher latent and sensible heat losses, especially to the atmosphere, but downward as well.

Soil stability is low during summer months because of steep moisture gradients associated with permafrost, especially on fine-grained soils.

Diesel fuel spilled at low intensities on meadow and beach ridge habitats on Devon Island killed exposed photosynthetic parts of vascular plants and mosses, but did not measurably affect lichens. Plants recovered partially the year following treatment because of the protection of many perennating buds shielded by exposed plant parts. The effects

of treatment on soil microbiota are not known.

Bi-weekly clipping of graminoids in a meadow community decreased above-ground yield by 20-30%. It is thought that greater decreases in yield will occur in subsequent years.

Treatment of beach ridge and meadow habitats on Devon with nitrogen, phosphorus, and potassium fertilizers showed that nitrogen and phosphorus increases production in many native species. There is an apparent mutual enhancement of effect by the two elements in combination. Potassium is thought to have no effect. It is not known whether the plant community changes which result from fertilization would be desirable on a long-term basis.

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INTRODUCTION

With industrial expansion in northern Canada and Alaska, there is increasing urgency for information on the immediate effects of environmental modification as well as on the long term capacities of natural systems to withstand disturbance. Because of the relative simplicity of High Arctic ecosystems, areas in the extreme North may be particularly sensitive to damage. As basic ecological enformation is sparse, a regional approach to the preliminary assessment of past and potential disturbance was in order. The area covered in this study included the northernmost islands in the Canadian Arctic Archipelago (primarily the Queen Elizabeth group, 75°-80°N, 70°-120°W.) and excluded the large islands adjacent to the North American mainland (Banks, Victoria, Prince of Wales, Somerset and Baffin).

The climate of the Archipelago is polar-maritime except in the interior of larger islands where a more continental climate prevails. This maritime condition plus the extreme northerly latitude of the islands results in mean growing season temperatures about 10° C. lower than in the continental Low Arctic. Precipitation is low (5-20 cm/year) in most regions with some exceptions in mountainous areas.

Parent materials vary from Precambrian granitics on eastern Devon and Ellesmere Islands to late Tertiary and Quaternary alluvium and drift of the Arctic Coastal Plain along the northeasterly margin of the Archipelago. Arctic platform sediments of Cambrian and Devonian age are exposed immediately

west of Shield granitics on Devon and Ellesmere Islands, but most of the Archipelago is comprised of uplifter Silurian through Tertiary sediments (Geol. Surv. Can. 1970).

Vegetation is primarily "fjaeldmark" or polar desert vegetation except in protected lowland sites where continuous "tundra" develops. Habitat diversity and consequently plant diversity is greatest near the coastlines on hilly and mountainous islands to the east.

Parent material, in addition to topography, can exert strong control on the character of some plant communities. The Beaufort formation, for example, a late Tertiary deposit exposed on much of Borden, Prince Patrick, and MacKenzie King Islands, is exceptionally barren (Savile 1961 and others).

To gain comprehensive information on the effects of vehicle travel and other types of potential use in a broad range of habitats, a combination of manipulation experiments in the Truelove Lowland on Devon Island and investigation of past disturbance at a number of industrial sites elsewhere in the Archipelago was undertaken. Objectives were to determine the character of impact and to assess the capacities of plant communities to recover.

REVIEW OF LITERATURE

Studies of the effects of surficial disturbance on tundra have been primarily in Low Arctic regions north of the Brooks Range in Alaska and in the Mackenzie Delta region in Canada. As most of the known "problems" associated with

disturbance have been physical, research has been oriented in this direction. Ferrians et al. (1969) discuss the engineering aspects of land use on permafrost terrain, and Mackay (1966, 1970, 1971) and others cover many of the dynamics of ground ice formation and interactions of vegetation with permafrost.

Because of the importance of vegetation to surface energy relations and to the shielding of ice-rich substrates from thaw, study of the biotic components of substrate dynamics is valuable. Brown et al. (1969) relate the effects of clipping, scraping and mulching to thaw depth and provide information on insulative capacities of various types of manipulated plant cover. Bellamy et al. (1970) take a direct approach in relating vehicle movements under controlled conditions to vegetational impact. The study is of practical use in minimizing destruction of plant cover, but says little about subsurface changes or long-term effects of microenvironmental alteration.

Secondary successional changes have been quantified by Hernandez (1972) on seismic lines and related disturbance in the Mackenzie Delta region, and by Pegau (1970) in 30 year-old clipped and denuded plots originally studied by Palmer and Rouse (1945) in west central Alaska. Tieszen et al. (1970) relate succession to indirect influences of disturbance on soil temperatures, microbial activity and soil nutrient regimes.

As development in the High Arctic has been only recent

the region has been largely inaccessible to study. Because of this and because damage to the sparsely vegetated terrain has not presented immediate and conspicuous environmental difficulties equivalent to those in the Low Arctic, little has been written about disturbance in the extreme North.

Local descriptive accounts provide useful information. Savile (1961,1964) discusses general habitat conditions, floristics and the effects of fertilization at Hazen Lake, Ellesmere Island and other High Arctic localities. Beschel (1963a, 1963b) provides useful background information on government activity and subsequent vegetational response in the vicinity of the Eureka airstrip, Ellesmere. Kevan (1971) describes in some detail the impact of vehicle use as well as rates and floristics of reinvasion in the vicinity of Hazen Camp. Bliss and Wein (1972b) discuss the definitive characteristics of High Arctic terrain units and their responses to physical disturbance in comparison with Low Arctic tundras.

MANIPULATION EXPERIMENTS ON DEVON ISLAND

Manipulation experiments were in conjunction with studies by the International Biological Programme Tundra Biome Study in the Truelove Lowland on Devon Island (see Appendix, III). Experiments included fertilization trials, spillage of diesel fuel on plant communities, controlled vehicle passage, simulated blading, and clipping to simulate intensive muskox or lemming grazing. Experiments were conducted in

two types of habitat, a xeric, raised beach ridge environment representing upland surfaces dominated by cushion plants and lichens, and in mesic meadow areas with continuous cover of mosses, sedges, and grasses.

Nomenclature of vascular plants here and in subsequent sections is according to Porsild (1964). Specimens are filed in the Herbarium of the University of Alberta (Dept. of Botany) or with the author.

Fertilization Trials

Methods

Trials were conducted on a raised beach ridge and in a mesic meadow. Plots 2 x 3 m were arranged in grid patterns with 2 m wide "buffer zones" separating individual plots. As the microhabitat within each of the two areas was too variable to allow all plots to be aggregated into single large groups, plots were broken into several smaller gridded clusters. These were treated with ammonium nitrate, "superphosphate", or potassium oxide fertilizers in granulated form in amounts equivalent to 56 or 336 kg/ha (50 or 300 lb/acre) of elemental N, P, or K respectively or with mixtures equivalent to equal amounts of the tree elements at total intensities of 56 or 336 kg/ha. Three replicates of each treatment were made totalling 24 treated plots in each habitat. In the meadow four additional plots isolated from those treated and located to represent unavoidable variation in microhabitat served as controls; three were established in the beach ridge

area. Fertilizer was applied July 6 and 7, 1970.

Plant growth was compared the following year on the basis of above-ground shoot production by dominant vascular species. Stem length increment of *Salix arctica* and shoot dry weight (80° C.) of *Carex stans* were measured in the meadow; shoot dry weight of *Dryas integrifolia* and *Saxifraga oppositifolia* and leaf dry weight and culm length of *Carex nardina* were measured on the beach ridge. Harvests were made August 1-20, 1971.

On all beach ridge plots on Aug. 18, 1971, soil samples for analysis for available N, P, and K were taken from a depth of 5-10 cm, sieved to 2 mm, and air dried. Analyses were by the Alberta Soil and Feed Testing Laboratory using standard techniques (Horwitz 1970). A duplicate set of samples was retained in moist condition at 0-5° except for a brief warm period in transit followed by freezing and storage upon arrival in Edmonton. This set was analyzed for available NH_4^+ and NO_3^- using a steam distillation process with magnesium oxide (Bremner 1965).

Also on the beach ridge, soil moisture percentage at a depth of 5-10 cm was determined gravimetrically on July 10. July 30, and August 18, 1971. Five subsamples per plot were mixed, sieved to 2 mm, and immediately placed in polyethylene bags to prevent water loss. Similar analyses were not made of the saturated peat soils in the mesic meadow site.

A "t" test was used in comparison of control and treatment production values. Pearson's correlation coefficient

(Pearson 1897) was used as a means of evaluating the importance of moisture with respect to individual plot production values.

Results and Discussion

Although data were not gathered the year of fertilizer application, it is noteworthy than no visible change occurred in the treated plots until the second season. The relative above-ground production of the five species measured at that time are given in Table 1. Plants showed significant responses to all elements. It is thought that the one significant response to potassium by *Carex stans* was the product of lateral movement of nitrogen and phosphorus during June snowmelt. Potassium levels were quite high in all control soils analyzed on Devon and other islands (Tables 2 and 3). The three elements combined appeared to have a greater than additive effect. Variability on treated plots was thought to be caused by "burning" rather than non-uniform fertilizer application.

Correlation of gravimetric moisture data with individual beach ridge plot production for all species showed no significant relationships ($r<0.1$ for all species). Moisture is therefore eliminated as a possible variable affecting the differences in production measured within the site. As the soil in the meadow was near saturation during the entire season, it is thought than moisture there was an equally insignificant variable.

Table 1. Effects of fertilizer treatment on plant growth on Devon Island one year following treatment. Confidence limits are set at P = .95.

Species	Measurement	N 56	N 336	P 56	P 336	K 56	K 336	N+P+K 56	N+P+K 336	Control
		Growth (% above controls)								
		Treatment (kg/ha)								
Carex stans	Shoot dry weight	-14±9	53±20 **	10±18	15±13	-15±10	44±20 *	14±23	82±28 **	0±12
Salix arctica	Stem length increment	3±18	18±22	-7±15	53±26 *	14±25	0±20	9±18	180±60 **	0±16
Carex nardina	Culm length	20±13 *	50±21 **	-13±10	40±11 **	0±10	14±9	48±12 **	37±9 **	0±6
Carex nardina	Leaf dry weight	35±25	-25±16	-23±10	35±18 *	-22±10	-17±10	40±15 *	35±15 *	0±15
Saxifraga oppositifolia	Shoot dry weight	131±42 **	153±44 **	38±17 *	201±54 **	34±17 *	16±16	276±60 **	288±42 **	0±12
Dryas integrifolia	Shoot dry weight	44±16 *	19±16	12±14	70±25 **	1±9	6±13	50±16 **	59±19 **	0±9

* Significantly different from control at P = .95
** Significantly different from control at P = .99

Table 2. Available soil nutrients and pH on beach ridge fertilized and control plots on Devon Island, August, 1971 (5-10 cm depth).

Treatment (kg/ha)	Available nutrients (ppm)					pH
	NH_4^+	NO_3^-	Total N	P	K	
N56	0.9	1.4	2.3	1.7	23.3	7.5-8.0
N336	1.7	16.3	18.0	2.7	23.7	" "
P56	0.5	0.8	1.3	2.7	20.7	" "
P336	0.4	0.7	1.1	18.7	22.0	" "
K56	0.6	0.7	1.3	1.7	27.0	" "
K336	0.4	o.7	1.1	3.3	48.0	" "
NPK56	0.4	0.8	1.2	2.7	22.7	" "
NPK336	1.5	3.5	5.0	10.0	38.0	" "
Controls	o.6	o.7	1.3	1.7	19.3	" "

Results were in partial accordance with the findings of Warren-Wilson (1957) who found that nitrogen increased production in pot tests with <u>Oxyria digyna</u> in soils from Cornwallis, N.W.T. Similarly Bliss (1966) in alpine communities in New Hampshire and Haag (1972) in the Mackenzie Delta reported increased production following fertilization of native communities with nitrogen. In these and in other studies, to the author's knowledge, similar responses to phosphorus alone in native communities have not been reported.

In contrast, Younkin (1972) found that agronomic species grown in Mackenzie Delta region soils responded positively to phosphorus while nitrogen affected production relatively little. Potassium had no effect. Dadykin (1958) demonstrated that while agronomic species show decreased utilization of nitrogen when grown in cold substrates, there is less inhibition of uptake and utilization of phosphorus and potassium. Such results indicate basic physiological differences in nutrient requirements or utilization capacities between temperate and arctic plants.

Lush plant growth on old, fertilized sites is a well known feature in the High Arctic; it indicates that nutrients in the soils are generally low, and than many native plants must be especially adapted to these levels. Russell <u>et al</u>. (1940) found that in soils on Jan Mayen Island inorganic nitrogen was an order of magnitude lower than in typical temperate grasslands. Levels reported by Russell are quite similar to those found in this study in a variety of undisturbed High Arctic soils (Table 3).

Table 3. Available soil nutrients and pH in soil samples from undisturbed or naturally manured sites on Devon and other islands.

Habitat or Disturbance	Site*	Available Nutrients (ppm) N	P	K	pH
Meadow	I-1	0.5	5.5	35.0	8.2
Meadow	VIII-1	0.0	7.0	17.0	7.2
Beach Slope (5cm)	I-2	0.5	7.5	105.0	7.7
Beach Slope (30 cm)	I-2	1.0	2.0	35.0	8.6
Saline Desert	VII	0.0	5.0	290.5	8.0
Muskox Trail	III-3	1.0	13.5	163.0	6.5
Garbage Barrels	III-6	12.0	9.0	78.0	7.5
control	III-6	1.5	1.5	33.0	7.1
Fox Den	I-3	0.0	25.0	65.0	7.7
control	I-3	0.5	7.0	56.0	8.0
Muskox carcass	III-4	0.5	11.5	94.0	7.1
control	III-4	0.0	1.5	49.0	6.8

* I = Bathurst; III = Devon; VII = MacKenzie King; VIII = Melville; see Appendix for detailed site descriptions.

The actual nutrient status of plants and soils on native arctic sites has rarely been reported. Results here indicate that phosphorus levels, in addition to nitrogen availability can be important. Analyses of soils at a number of older sites manured by animal remains or droppings show that available phosphorus is sometimes considerably higher where "lush growth" has resulted while nitrogen availability is not necessarily greatly different from controls (Table 3). Low nitrogen readings may, however, be an artifact of sampling and storage methods, or the result of a thorough depletion of inorganic nitrogen by higher plants, an effect noted by Russell et al. (1940) in a late snowbank community during a period of rapid growth.

Low phosphorus may be limiting in more High Arctic communities than has been previously thought. On the Devon Island sites this could best be attributed to the high pH and high magnesium and calcium content of most soils (Peters and Walker 1972). Under such conditions phosphorus would probably be unavailable through the formation of insoluble calcium phosphates (Buckman and Brady 1969). As reported by Tedrow (1966), similar conditions are prevalent over much of the High Arctic. This is most likely a function of low organic content of polar desert soils, subsequent low levels of organic acids, and the widespread occurrence of calcareous sediments and tills.

A possible explanation for the apparent greater than additive effect of combined nutrients is that nitrogen and

phosphorus could be concurrently limiting. Adding either nutrient by itself results in slightly accelerated growth until demands for the other inhibit further increase. When both are sufficiently available, ultimate limitations are imposed by other environmental or genetic factors (Fried and Broeshart 1967).

Fertilization data and field observations on Devon indicate that certain species are affected more than others by changes in nutrient levels. Though it was not quantified, Alopecurus alpinus and Arctagrostis latifolia showed much more conspicuous growth with combined N, P, and K one year after treatment than did sedges and rushes. On older, fertilized sites such as around muskox carcasses or on bird perches Cerasteum alpinum, Salix arctica, and Papaver radicatum grow much more vigorously than elsewhere.

While growth of some species is stimulated, that of others may ultimately be repressed. Most lichens disappeared in the immediate vicinity of muskox carcasses investigated, and some vascular species died back (e.g. Dryas integrifolia, Table 10 pg. 35, and Cassiope tetragona at a site for which the data are not presented here). Savile (1972) thinks that arctic plants are adapted to low nutrient levels to the degree that greatly increased nutrients would be harmful. A number of species exhibit what he considers to be symptoms of excess nitrogen under nutrient and climatic regimes normal for temperate region plants. Sorensen (1941) attributed preferential takeover by some species to a competetive mechanism

but not necessarily to pathological effects of high nutrient levels. Production in species capable of utilizing relatively large amounts of nutrients is great when essential elements are abundant. Other species are incapable of greatly increasing production above a low level commensurate with the low nutrient regimes to which they are adapted (i.e. those prevalent over most of the High Arctic). Thus species of the latter type are at a competetive advantage when fertility is high. Competition for moisture, nutrients, space, and light as well as allelopathic interactions may be involved.

Sorensen did not support his hypothesis with experimental data, but the results of this experiment do agree with his suggestion. _Dryas integrifolia_, for example, would fall into the second category, for it responded relatively little to fertilization and does disappear on older fertilized sites. More detailed autecologic and community information is needed.

Worthy of further investigation is the long-term effect of manuring. In the vicinity of one muskox carcass _Salix arctica_ had annual stem length increments 3 to 5 times that of nearby shrubs for at least 13 years (disturbed = 36 $\pm$ 8 mm; control = 7 $\pm$ 1.2 mm at P = .95). These plants may be capable of assimilating nutrients when they are available and of minimizing losses thereafter. Another possibility is that nutrients may initially be taken up by soil microorganisms, then released slowly over long periods (Tieszen _et al_. 1970). Nutrient requirements and mechanisms of cycling are not well known.

It is important to note that much of the impact of "fertilization" may not be directly related to inorganic nutrients *per se*. Although these are probably of prime importance, changes in humic content, pH, water retention capacity, and interspecific interactions may also be involved.

Diesel Fuel Spills

Methods

Plant surfaces in meadow and beach ridge communities were treated with diesel fuel on August 12, 1970. Three replicate 2 x 3 m plots per treatment in each community were sprayed with oil at intensities of .05 and .25 l/m^2. At the higher intensity, slightly more than enough was applied to cover the ground and all foliage. Three identical and untreated plots served as controls.

Plant growth was monitored in 1971 using the same methods as for the fertilization trials (see above pg. 5). Cover was measured near the end of the 1971 season for comparison of ratios of living to dead tissue in treated and control plots. A first-point contact method was used with 20 randomly placed frames of 10 points each per plot.

On the beach ridge plots where lichen cover was important, samples of two species, *Thamnolia vermicularis* and *Umbilicaria lyngei* were taken for comparison of vitality through respiration measurements. Approximately 2 grams of each were harvested on August 18, 1971 from a control and from a plot treated with .25 l/m^2 of diesel. These were stored in air-

dry condition for 11 weeks. One week prior to respiration measurement, the thalli were placed in an illuminated growth chamber where temperature fluctuated from 5° to 15° on a 24 hour cycle. They were kept moist during this period with distilled water. Respiration was measured at 0° , 5°, 10°, and 15° by Warburg manometry. Techniques were standard (Umbreit *et al*. 1957) except that the 0.1 g thallus samples used were placed moist but free in the flasks rather than suspended in a carrier solution.

Results and Discussion

The dry weights of shoots of treated *Dryas integrifolia* and *Saxifraga oppositifolia* were slightly greater than those from control plots on the beach ridge. Though shoot production of *Carex stans* in the meadow was not affected, *Carex nardina* leaf dry weight on the beach ridge was significantly low at the higher intensity of treatment (Table 4).

Respiration in lichens from treated plots was similar to controls. Rates were comparable to chose previously reported for *Thamnolia vermicularis* and species of *Umbilicaria* from Alaska (Scholander *et al*. 1952).

Because of its relatively low viscosity and low volatility, diesel fuel is one of the more toxic industrial hydrocarbon mixtures. It has a high wetting power and remains on a site much longer than fuels such as gasoline (Klingman 1961). Like many oils, it can block stomata, penetrate the cuticle, dissolve plasma membrane, disrupt cytoplasmic membranes, and extract certain cell components (Klingman 1961,

Table 4. Effects of diesel fuel on growth of shoots or leaves in mesic meadow and beach ridge habitats one year after treatment, Devon Island. Confidence limits are set at P = .95.

Species	Habitat	Measurement	Shoot Growth (% above controls)		
			.05 l/m^2	.25 l/m^2	controls
Dryas integrifolia	Beach Ridge	Shoot Dry Weight	0±18	34±18*	0±10
Saxifraga oppositifolia	Beach Ridge	Shoot Dry Weight	19±12	32±24	0±13
Carex nardina	Beach Ridge	Leaf Dry Weight	-10±12	-20±7*	0±9
Carex stans	Mesic Meadow	Shoot Dry Weight	3±12	-5±18	0±20

* Significant at P = .95

Baker 1970). The degree of damage depends upon the physical characteristics of the species as well as the physiological and phenological condition of plants at the time of treatment.

When oil was applied almost all exposed photosynthetic tissue of vascular plants was killed. The green parts present when cover was measured the following year (Tables 5 and 6) probably grew from protected perennating buds. In the woody perennials (Dryas and Saxifraga) the greater than normal shoot weights from treated plots may be the product of a greater proportion of overwintering carbohydrate reserves being available per surviving bud.

Mosses are either more resistant to damage or are more capable of recovering from damage following application of fuel at the relatively low intensities used here.

It is possible that more persistent or more deeply penetrating hydrocarbon films could be harmful to lichen thalli. Some types of crude oil contain hydrogen sulfide or other sulfur compounds which, when oxidized to sulfur dioxide, are highly toxic to lichens (Hale 1967, Hamilton 1971). Spontaneous oxidation of spilled crude oil or flaring of natural gas could therefore affect lichen production over large areas.

It has been observed that there is a burst of microbial activity and increased nitrogen content in soil some time after petroleum products (including natural gas) have been introduced. Soil redox potentials can be altered, and this can result in increased manganous and ferrous ions in the

Table 5. Mean cover (%) in control and diesel treated mesic meadow plots, Devon Island, August 12, 1971.

Species or Cover type	Cover (%)					
	control		.05 $1/m^2$		.25 $1/m^2$	
	live	dead	live	dead	live	dead
Arctagrostis latifolia	2.0	0.8	1.7	1.5	0.8	0.3
Carex membrenacea	15.3	15.0	7.7	14.3	7.7	24.8
Carex misandra	1.7	-	-	-	-	1.2
Carex stans	1.8	1.3	3.3	2.8	0.7	0.8
Equisetum variegatum	0.2	-	0.5	-	-	-
Juncus biglumis	6.8	1.7	9.0	3.8	4.0	1.7
Pedicularis sp.	0.3	-	1.0	-	-	-
Polygonum viviparum	4.3	1.0	4.3	1.2	0.7	1.5
Salix arctica	4.7	1.0	4.7	1.8	3.4	2.3
Saxifraga hirculus	0.2	-	1.6	-	-	-
Nostoc sp.	0.7	-	2.0	-	2.7	-
lichens	-	-	-	-	-	-
mosses	39.3	-	37.2	-	45.3	-
dung	-	1.2	-	-	-	0.8
total vascular plants	38.0	20.0	35.8	25.4	20.0	32.6

Table 6. Mean cover (%) in control and diesel treated beach ridge plots, Devon Island, July 18, 1971.

Species or Cover type	Cover (%)					
	control		.05 l/m^2		.25 l/m^2	
	live	dead	live	dead	live	dead
Carex nardina	0.5	-	0.3	0.3	0.7	0.7
Cassiope tetragona	2.0	-	2.0	3.3	1.3	3.0
Dryas integrifolia	4.2	9.5	2.7	6.8	3.2	12.5
Luzula nivalis	0.2	-	0.2	0.2	0.2	-
Pedicularis sp.	-	-	-	-	-	-
Salix arctica	1.5	-	0.7	-	0.2	-
Silene acaulis	-	-	0.5	-	0.2	-
Saxifraga oppositifolia	1.3	3.0	1.7	3.3	2.5	1.3
mosses	3.0	1.5	5.5	0.7	3.8	1.2
crustose lichens	55.2	-	56.3	-	51.3	-
foliose lichens	6.8	-	7.3	-	8.8	-
fruticose lichens	12.8	-	14.0	-	12.7	-
bare rock	-	5.8	-	4.8	-	5.2
bare soil	-	2.0	-	1.3	-	2.7
litter	-	4.8	-	4.3	-	5.7
dung	-	0.3	-	-	-	-
total vascular plants and mosses	12.6	14.0	13.6	14.6	12.1	18.7

soil, sometimes with toxic effects from the manganese (Adams and Ellis 1960, Ellis and Adams 1961). Depending on how much oil actually penetrated the soil, this could actually be the case here. In the meadow plots a greater proportion of the fuel was absorbed by vegetation and litter than on the beach ridge, and effects within the soil may therefore be less.

Controlled Vehicle Passage

Methods

In a level mesic meadow on July 13, 1971, 10, 40, and 60 passes were made with a "Ranger" tracked vehicle. The vehicle had cleated rubber tracks and a surface load of approximately 0.5 psi. Thaw depth was measured with 20 probes in each treated and area and adjacent control at weekly intervals thereafter until August 24.

Results and Discussion

Surface compaction amounted to a maximum of 5 cm where 60 passes were made. With less intense treatment, compaction was correspondingly less. With up to 60 passes there was no observable change in cover and little breaking of turf. Depth of the active layer was not significantly increased with this amount of disturbance (Table 7). Measurements in vehicle tracks at Pt. Barrow showed an average increase in thaw of 50% (Tieszen _et al_. 1970). Similar effects were reported by Bliss and Wein (1972b) in the Mackenzie Delta region. Surface disturbance in these instances was more severe, and was

Table 7. Thaw depths at weekly intervals within test and adjacent control areas in a mesic meadow where controlled vehicle passes were made, Devon Island, 1971. Standard errors are all less than 5% of means.

Date	Thaw Depths (cm)					
	10 passes	C*	40 passes	C	60 passes	C
July 15	25	26	20	23	25	23
July 22	29	30	26	29	29	32
July 31	24	30	29	28	39	32
Aug. 8	32	33	29	31	34	32
Aug. 15	34	34	30	31	35	36
Aug. 24	34	35	30	31	34	34

* C = control

on a substrate which probably had warmer permafrost and a higher ground ice content.

In a similar but wetter area where an estimated 150 passes had been made by the same vehicle plus a trailer, a 30 cm deep, water-filled rut formed. There is apparently a threshold level of tolerance of the rhizomatous turf on these silty soils. In areas where vegetation is capable of withstanding several passes of a light vehicle it is advisable not to use a single roadway, but to restrict use in a given area to travel intensity below such a threshold level. Where heavier vehicles are used a single pass can have long-lasting damaging effects. Natural recovery in such sites will be discussed below (see pp 34-37).

Simulated Blading

Methods

On three replicate 2 x 3 m plots in a mesic sedge meadow all vegetation and the top 2-3 cm of soil were removed (July 6, 1970). Depth of thaw was measured weekly from July 19 to August 22, 1971 in treated and adjacent control plots. In late August during a three day interval free of visible cloud cover, energy flows in the plots were recorded. An energy budget for a 24 hour period was determined. Net radiation was measured using Funk net radiometers, albedo using Kipp and Zonen albedometers, soil heat flux with Thornthwaite flux plates, and temperatures with thermisters and a Grant 9-probe

recorder. Except for temperatures, data were recorded using an Esterline Angus potentiometric recorder. Outgoing longwave radiation was calculated from net radiation and albedo data, and the remainder of dissipated energy, which is made up almost entirely of convective transfer and latent heat loss from evapotranspiration, was estimated from these as one block of energy.

Results and Discussion

Table 8 and Fig. 1 give energy budgets and soil and air temperature profiles respectively over the 24 hour period. Weekly changes in thaw depth over the 1971 season in treated and control plots are represented in Fig. 2.

In this experiment removal of vegetation approximately halved the amount of shortwave solar radiation reflected (albedo). The amount of longwave reradiation increased slightly on the scraped plot, as did convective and evaporative heat loss. These accounted for the dissemination of most of the increased energy absorbed; the result was a relatively small increase in soil heat flux and subsequent thaw.

Soil temperatures fluctuated more on the scraped surface, but on the average were slightly in the control plot (means were 3.5^{o} and 4.4^{o} for hourly point readings on treated and control surfaces respectively). These do not correspond to the lower heat flux values in the control. The discrepancies may indicate differences in thermal conductivity in the two substrates, or may be the result of the placement of sensors.

Table 8. Energy flow rates over a 24 hour cloud free period in late August on scraped and control mesic meadow plots, Devon Island, 1971. Means are calculated from point readings taken at hourly intervals.

		Energy Flow Rates (gm cal/cm^2/min)						
Treatment	Time	Incoming shortwave	Reflected shortwave	Absorbed shortwave	Outgoing longwave	Net radiation	Soil heat flux	Convection, evapotranspir-ation, etc.
	0500	+.211	-.015*	-.227*	-.031	-.031	+.011**	+.020
	1200	+.602	-.052	+.550	-.224	+.326	-.065	-.261
Scraped	1800	+.312	-.021	+.291	-.213	+.078	-.016	-.062
	2400	.000	.000	.000	-.078	-.078	+.030	+.048
	mean	+.295	-.022	+.273	-.185	+.088	-.006	-.082
	0500	+.211	-.024	+.187	-.187	.000	+.020	-.020
	1200	+.602	-.109	+.493	-.221	+.272	-.046	-.226
Control	1800	+.312	-.033	+.279	-.249	+.030	-.006	-.024
	2400	.000	.000	.000	-.070	-.070	+.020	+.050
	mean	+.295	-.049	+.246	-.176	+.070	+.002	-.072

* estimated values

** A positive value (+) indicates a net upward flow of sensible heat

Figure 1. Soil and air temperatures over a 24 hour period in late August in scraped and control plots in a mesic meadow on Devon Island.

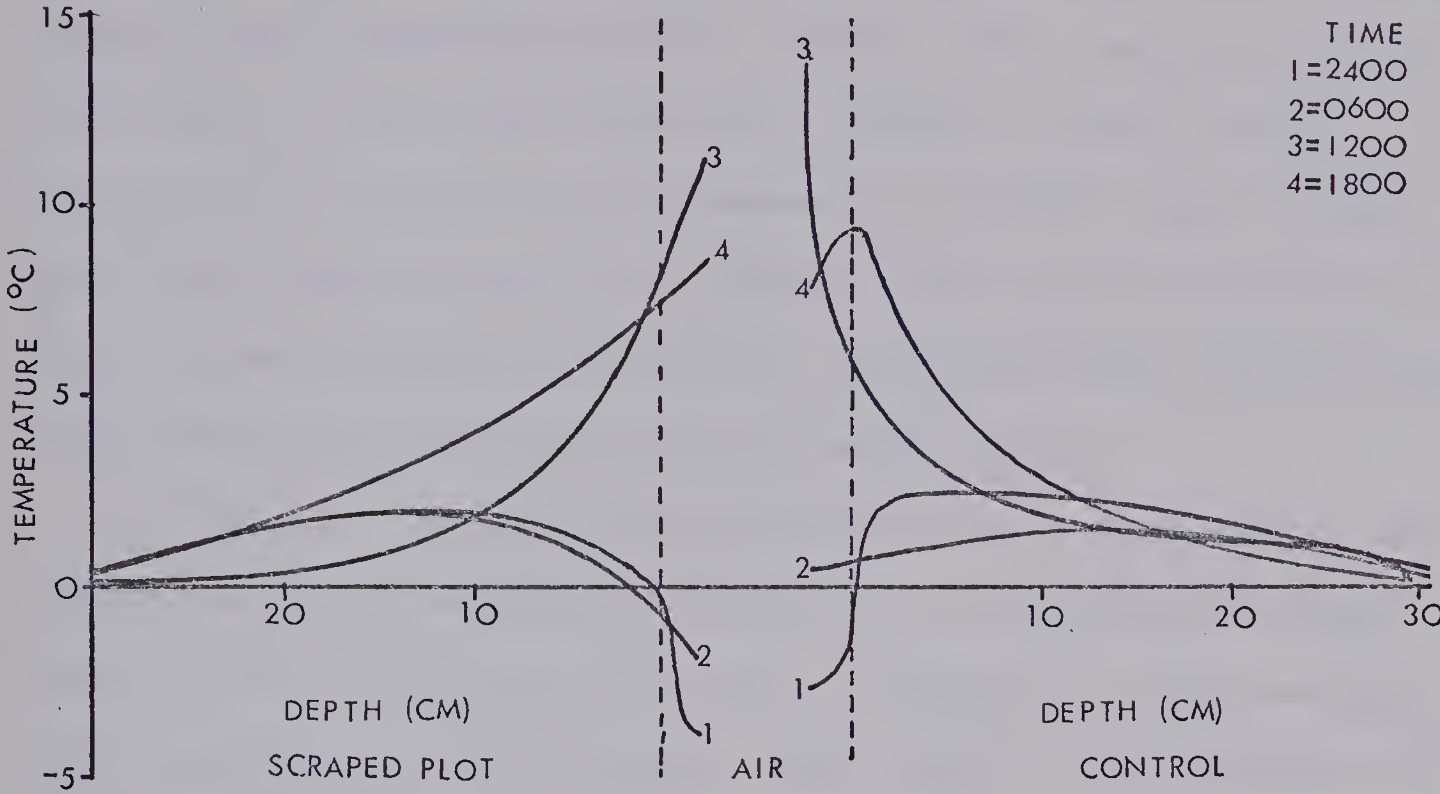
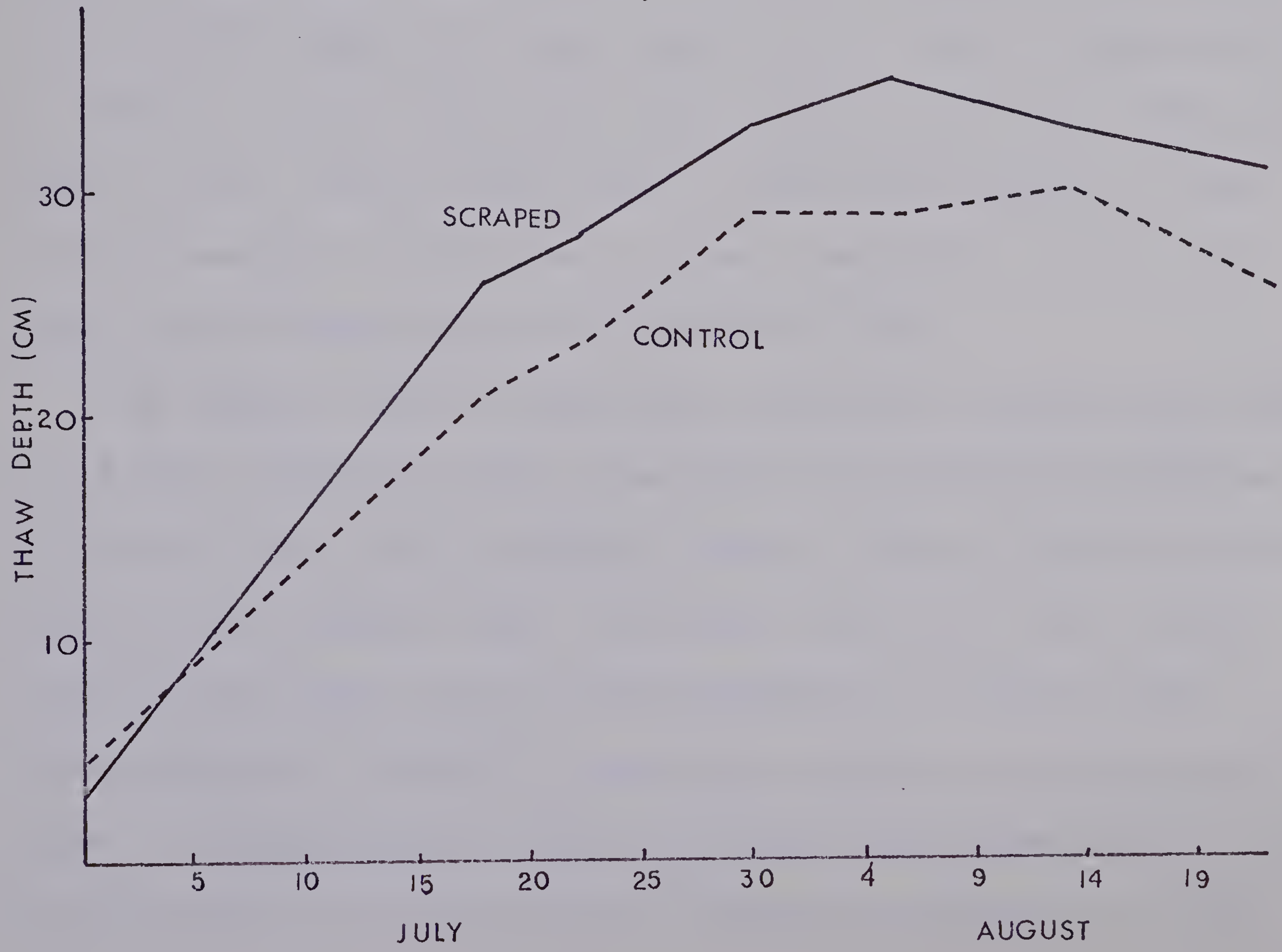


Figure 2. Changes in thaw depth over the growing season in scraped and control plots in a mesic meadow on Devon Island, 1971.



Although latent and sensible heat loss to the atmosphere was greater in the treated plot, air temperatures were higher close to the vegetated control surface (air temperature sensors were at 2 cm above the soil surface in both plots). This may be the effect of a community boundary layer within which air temperatures are somewhat higher than ambient but which slows sensible and sensible and latent heat loss to the atmosphere by inhibiting mass movement of air.

It is well known that engineering and environmental difficulties can arise from the melting of permafrost brought about by the disturbance of arctic vegetation (Ferrians _et al_. 1969, Mackay 1970 and others). The energy relationships of this effect are not as well known. Brown _et al_. (1969) in Alaska found that the removal of tundra vegetation and peat can increase depth of summer thaw by over 100%. Replacement of both as a mulch decreased this effect only 40%. Thus plant cover is not acting simply as an insulative barrier to the flow of energy into the soil; other components of the surface energy budget must be affected as well.

It appears that an important difference between High and Low Arctic tundras is that thaw and the associated problems are less in the more northerly regions (see pp. 42-43 below). Results here suggest that a primary reason for this difference is that heat loss to the atmosphere in colder areas counteracts the effect of decreased albedo on disturbed surfaces. Meteorological data from Inuvik and Norman Wells in the Low Arctic and from Alert, Eureka and Resolute in the

Archipelago show that mean air temperatures are about 8° warmer during June, July and August in the southern region (Can. Met. Serv. 1971). The number of hours of bright sunshine during the same period averaged 293 hours per month at the Low Arctic stations versus 328 hours per month at the northern locations in the summer of 1971. If the latter can be taken as an acceptable, though crude, index of summer insolation, it indicates that differences in incoming radiation are not in themselves sufficient to account for differences in sensitivity of permafrost to surface disturbance. The greater insulative effect of community boundary layers on more lushly vegetated Low Arctic tundras is probably important, as may be greater rates of evapotranspiration with denser, taller plant cover and higher air temperatures. Also perhaps significant are higher permafrost temperatures (Brown, R.J.E 1972) and longer snow-free periods farther south. Much more information is needed before detailed comparisons can be made.

Clipping Experiment

Methods

Three replicate sets of three contiguous 1 m^2 plots were established in a mesic sedge meadow. Cover consisted primarily of mosses and *Carex stans* with some *Eriophorum triste*, *Polygonum viviparum*, *Salix arctica*, *Arctagrostis latifolia*, and *Equisetum variegatum*.

At the beginning of the growing season all graminoid

foliage (mostly dead) and litter were removed from above moss level in two of each set of three plots. This was oven-dried (80° C.) and weighed. A 0.3 m buffer zone around each plot was clipped and cleared as well. At two week intervals all foliage was harvested by clipping at moss level in the second of each pair of previously cleared plots. At the end of eight weeks, material in the first and second plots was harvested as previously, as was all green and standing dead graminoid material and litter in the third (control) plots.

Results and Discussion

In all replicates the total dry matter above-ground yield from July 1 to August 26, 1971, was 20-30% lower in the plots clipped bi-weekly than in the plots clipped only on July 1 (Table 9).

Responses to clipping in temperate grasslands differ; in some instances growth and production are temporarily stimulated (Albertson et al. 1953), and in others growth rates decline (Mueggler 1967). In most instances the species or communities clipped are adversely affected by death or reduction of underground parts (Albertson et al. 1953, Mueggler 1967, Neiland et al. 1956) or by decreased carbohydrate reserves as affected by decreased photosynthetic surface (Jameson 1963).

One of the most important adaptations of arctic and alpine plants to short growing seasons is the capacity to store carbohydrate and lipid reserves for an early burst of

Table 9. Mean above-ground production in plots clipped once or at bi-weekly intervals in a mesic sedge meadow community, Devon Island. The means for the bi-weekly clipping values (row 4 in the table) are expressed as percents of final plot 1 harvests in paired plot arrangements. Confidence limits are at P = .95.

Treatment	Above-ground Production (gm/m^2)					
	July 1	July 15	July 29	Aug. 12	Aug. 26	Total
Clipped once	57.5	-	-	-	24.9	24.9
Clipped bi-weekly	57.5	8.0	7.7	2.8	0.2	18.7
Control	-	-	-	-	52.2	-
Bi-weekly means	-	32%±4.6	31%±3.4	9%±2.4	1.3%±0.4	76%±9.8

growth following snowmelt (Bliss 1971). A maximum of photosynthetic tissue is thus exposed for much of the growing season, and effeciency of utilization of total available sunlight is enhanced. Although yield in intensely clipped plots dropped only 20-30% the first year, it is probable that reduced carbohydrate reserves in roots and rhizomes will result in further yield reduction subsequently. This will depend in part on the degree to which carbohydrates are translocated through underground parts from areas outside the buffer zone.

INVESTIGATIONS OF PAST DISTURBANCE ON DEVON AND OTHER ISLANDS

Work during the 1970 and 1971 seasons included plant cover comparisons on disturbed and undisturbed surfaces, field descriptions of soil profiles, measurement of soil temperature profiles and qualitative descriptions of topography, geomorphology, and general environmental conditions. Data were obtained at approximately 30 specific sites at camps or areas of human habitation on Bathurst, Devon, Cornwallis, Ellesmere, Ellef Ringnes, King Christian, MacKenzie King, and Melville Islands.

Methods

Cover by species of vascular plants and of lichens, mosses or bare soil as cover types on disturbed and undisturbed (control) surfaces was estimated using a square quadrat frame (40 x 40 cm) gridded into sixteen (10 x 10 cm) subunits. Cover within each of 10-20 random placements of the frame per area was determined visually.

During the 1971 season field descriptions of soil profiles were made at most sites where plant cover was determined. Nomenclature and terminology of the Canadian System of Soil Classification were used in descriptions (Can. Dept. Ag. 1970). Determinations of pH were made using a Truog indicator kit, and colors were according to Munsell standards. Soil temperature profiles were measured using a portable nul-

ling resistance bridge and a series of 5 diode sensors mounted at 15 cm intervals in a tubular nylon probe. Four or five probes were made in each area. Thaw depth was measured in disturbances and controls using 20 probes per area with a calibrated steel rod.

Results and Discussion

For general descriptions of habitat and impact of recent disturbance in the areas visited, as well as more specific descriptions of sites referred to in tables and text, please see the Appendix.

At most of the sites studied, disturbance was too recent for measurable recovery to have occurred. As detailed quantitative descriptions of impact on these does not relate directly to the discussion here, they have been tabulated separately and filed with the author.

From older sites rates of vegetative recovery can be inferred. Cover by species on disturbed and control surfaces at eight dated sites representative of variations in High Arctic plant habitats are given in table 10.

The ages, nature of disturbance, approximate site characteristics and locations of these were as follows:

1. A ten year-old tractor trail on a raised beach ridge, Truelove Lowland, Devon Island, Aug. 11, 1970, (Appendix, III-1).
2. A ten year-old tractor trail in a mesic meadow, Truelove Lowland, Devon Island, Aug. 11, 1970, (III-2).
3. A two year-old abandoned airstrip on sandy soil on

the Sabine Peninsula, Melville Island, July 24, 1970 (VIII-3).

4. A zero to three year-old set of vehicle tracks on a meadow on the Sabine Peninsula, Melville Island, July 24, 1970 (VIII-2).
5. A ten to twenty year old site scraped for airstrip landfill, semi-desert, Eureka, Ellesmere Island, July 31, 1971 (V-4).
6. A fox den site of unknown age, semi-desert, Freeman's Cove, Bathurst Island, July 16, 1970 (II-3).
7. A muskox carcass 13 to 20 years old on a raised beach ridge near a rock outcrop, Truelove Lowland, Devon Island, Aug. 5, 1970 (III-4).
8. A two to four year-old muskox carcass on a mesic site in a rock outcrop, Truelove Lowland, Devon Island, Aug. 10, 1970 (III-5).

In the more xeric polar desert or semi-desert sites which prevail in the High Arctic ("silt crust" terrain, beach ridges, sandy areas etc.) low temperatures and desiccation appear to be more limiting than biotic factors. An established plant community, even when mature, has a relatively small effect on the general habitat. Thus autogenic processes are probably not as important in succession as they are in less hostile environments. "Succession" in such areas tends to be a slow, one-step process of reinvasion by species previously present. There are usually no conspicuous seral "stages" as plant cover is reestablished. The length of time required

Table 10: Cover on disturbed (D) and control (C) surfaces on High Arctic islands (Key to sites page 33).

Species	Cover*															
	Site															
	1		2		3		4		5		6		7		8	
	D	C	D	C	D	C	D	C	D	C	D	C	D	C	D	C
Arenaria rubella	+															
Carex nardina		1														
Silene acaulis		+														
Draba spp.	1	+			1	+			+	+	1	1	+	+	+	+
Papaver radicatum	1				1				+	+	2	+	+			
Saxifraga oppositifolia		2										2	1	+	1	2
Dryas integrifolia		2										2	1	4	2	3
Cassiope tetragona																+
braya purpurascens					+											
Agrostis latiglume									1	1						
Deschampsia brevifolia									1	+						
Cerasteum alpinum	+										2	+	1			
Cerasteum beeringianum									+	+						
Melandrium triflorum									+	+						
Oxyria digyna	+				1				+	+		+			1	1
Polygonum viviparum	+	+											1	+	2	1
Potentilla hyparctica					+	+										
Potentilla rubricaulis									+	+						
Puccinellia angustata									4	2						
Stellaria longipes									+	+		+				
Salix arctica	1	2		1		1		5	+	3		3	2	+	2	2
Pedicularis spp.	+	+											+		2	2
Luzula confusa					3	5										
Luzula nivalis											2				1	+
Poa abbreviata											+					
Carex misandra													5	3	2	3
Epilobium latifolimm													3	+		
Saxifraga caespitosa											1					
Saxifraga cernua												+				
Saxifraga rivularis											+					
Saxifraga nivalis					+						+					
Festuca brachyphylla											2	+				
Alopecurus alpinus					1	2		1	+	+	6					
Cochlearia officinalis											+					
Ranunculus sabenei											1					
Arctagrostis latifolia				2											1	+
Poa alpigena							+	3								
Equisetum variegatum				2												
Carex stans			+	3			+	5								
Eriophorum triste			1	3												
lichens	+	4			+	+						5	+	5	+	1
mosses		+	2	6		2	+	5			3	1	4	1	2	3

* Cover classes: +=<1%; 1=1-2%; 2=2-5%; 3=5-10%; 4=10-20%; 5=20-50%; 6=50-100%.

for recovery depends upon the growth rates of the species involved plus the period required for the initial establishment of young plants. Recovery can take perhaps 5 to 100 years depending upon whether local dominants are quickly established and fast-growing (e.g. Puccinellia angustata and Deschampsia brêvifolia, Table 10), or slowly established, long-lived and slow-growing (e.g. Salix arctica and Dryas integrifolia). The establishment, growth, and death of plants in such fjaeldmark communities is discussed by Wager (1938) and Raup (1969).

In general, species which reinvade most rapidly on these dry sites are efficient seed or bulbil producers (Papaver radicatum, Draba spp., Saxifraga spp., several grasses, Oxyria digyna, Polygonum viviparum, and others). Slow invaders are woody perennials, which grow slowly and appear to establish seedlings only on very rare occasions (Salix arctica and Dryas integrifolia), and lichens. Mosses are usually present in protected micro-sites and reestablish themselves readily in such sites following disturbance. Where they depend on cushion plants and mat formers for protection, they invade concurrently with these vascular species.

Succession on more mesic or hydric sites has been difficult to assess. Natural reseeding is not common. The prevalent mechanism observed is lateral invasion by rhizomes from the rootstocks of sedges and grasses in adjacent undisturbed areas. In many instances this appears to proceed very slowly (sites 2 and 4, Table 10). In vehicle tracks in meadow areas most sedges and grasses do not seem to grow successful-

ly until the depression formed has been obliterated by siltation, accumulation of peat, or by frost action. In many areas mosses play a more important role in initial reinvasion than do vascular plants.

Perhaps important with regard to this are the findings of Kershaw (1966) in Iceland. Although the rhizomes of *Calamagrostis neglecta* and *Carex bigelowii* were found to grow more or less randomly, they tillered (sprouted) in a clumped manner; plantlets were significantly aggregated. This behavior is apparently stimulated by environmental conditions in the vicinity of a group of plantlets, but the stimulus is unknown. The marked absence of tillers in old vehicle tracks may be due to the requirements for such a stimulus in the tillering of many rhizomatous species.

Knowledge of High Arctic soil characteristics is necessary in understanding the effects of disturbance. An essential feature is the infrequency of deep peat accumulations and the preponderance of mineral soils (Tedrow 1966, Bliss and Wein 1972c). Tedrow (1966, 1968) discusses some of the dynamic processes in High Arctic regions. Soil characteristics are due primarily to low temperatures (which slow chemical weathering processes), frost action (which disrupts any pedogenic horizonation which may occur), and permafrost (which inhibits drainage). Wind erosion, salinization, and the sparseness of higher plants as a source of organic matter are also important factors.

Three profiles from a cold polar desert site (Profile 1),

a warmer polar desert site (Profile 2), and a meadow site in a warmer High Arctic region (Profile 3) are described below.

Profile 1. (July 17, 1971)

Location: Hoodoo Dome airstrip, Ellef Ringnes Island, N.W.T

Parent Material: Weathered sediments, unstratified silt, sand, and clay mixed by frost action.

Landform and Site Position: Depressional to level upland surface, about 8 meters above present drainage of local watercourse about 2/3 km distant.

Profile Drainage: Imperfectly drained.

L: Discontinuous sedge and dicot herb leaf litter; lichens.

C: 0-55 cm; loam grading to clay loam grading to clay; brownish black (10YR 3/2); massive structure; firm grading to sticky consistence; neutral, grading to very slightly acid pH (7-6).

Cz: 55 cm; clay and clear ice; brownish black (10YR 2/2); fluid when melted; smooth horizon boundary; very slightly acid pH (6).

Profile 2. (July 30, 1971)

Location: Ten km east of Romulus Lake, Fosheim Peninsula, Ellesmere Island, N.W.T.

Parent Material: Weathered sediments and till, unstratified silt and sand mixed by frost action.

Landform and Site Position: Gently sloping upland surface; area of broad, low hills (1-3 km x 20-50 m).

Profile Drainage: Moderately well to imperfectly drained.

C: 0-50 cm; loam grading to silty loam; dull yellow orange (10YR 6/4) grading to dull yellowish brown (10YR 5/3); very weak, fine granular structure; slightly hard consistence at surface; firm consistence in lower horizon; plentiful fine roots in the upper 10 cm grading to very few fine roots at the base of the horizon; few small pebbles; alkaline pH (8).

Cz: 50 cm; frozen silty loam; grayish yellow-brown (10YR 4/2); massive structure; firm consistence when melted; few small pebbles; alkaline pH (8).

Profile 3. (July 30, 1971)

Location: Three km south of the mouth of the Slidre River, Fosheim Peninsula, Ellesmere Island, N.W.T.

Parent Material: Weathered sediments, unstratified silt and sand mixed by frost action.

Landform and Site Position: Strongly sloping north facing slope, fifty m south of steep slope of 20 m high ridge.

Profile Drainage: Imperfectly to poorly drained.

LFH:0-1 cm; woody perennial, sedge, grass, and moss litter, fibre and humus.

C: 1-4 cm; silt loam; brownish gray (7.5YR 6/1); massive structure; non-plastic consistence; plentiful fine roots.

Cg: 4-45 cm; silt loam and masses of partially decomposed peat; grayish brown (7.5YR 5/2) with common, coarse distinct dull brown (10 YR 5/3) mottles; massive structure; non-sticky consistence; few fine roots.

Cz: 45 cm; silt loam and clear ice; grayish brown (7.5YR 5/3); massive structure; non-sticky consistence.

Soil profiles 1 and 2 have been tentatively classified as Cryic Regosols, and number 3 as a Gleyed Cryic Regosol. It should be noted that there is a slight change in texture from the surface of the C horizon and an accompanying increase in strength of a very weak granular structure. Beschel (1963a) in discussing geomorphic processes in the region where Profile 2 was described indicated that mass movement (primarily amorphous solifluction) and related processes appear, for the present to have declined in rate. Thus slow processes of pedogenic horizonation normally inhibited by "frost action" may thus be in juvenile stages.

Although there are doubtlessly innumerable variations in stoniness, texture, and salinity, these profiles represent the basic characteristics of low peat content, poor horizonation, and impaired drainage of the High Arctic soils observed in this study or reported in the literature.

Some of the energy relations of disturbed and undisturbed surfaces can be inferred from cover, thaw depth, and soil temperature data (Table 11). Temperature profiles illustrate several effects. Differences in surface temperature were never great between disturbed and control surfaces. The direction and magnitude of differences was variable and depended primarily on weather conditions and time of day. Compacted and devegetated surfaces were cooler than controls when air

Table 11. Cover and associated thaw depth and soil temperatures on disturbed (D) and control (C) surfaces on Ellef Ringnes and Ellesmere Islands. July, 1971.

Location	Site	Date	Total cover by class*		Thaw depth (cm)		Temperature (^{o}C.)					
							surface		15 cm depth		frost	
			D	C	D	C	D	C	D	C	D	C
Ellef Ringnes,	1	17/7	3	4	30	27	5.8	7.0	2.4	2.6	-0.6	-0.6
Hoodoo Dome	1-b	17/7	4	5	34	27	4.6	7.0	2.4	2.6	-0.6	-0.6
(IV-a)	2	18/7	4	5	37	34	7.4	6.8	2.4	2.0	-0.4	-0.4
	2-b	18/7	5	5	36	34	7.2	6.8	1.9	2.0	-0.6	-0.6
	3	19/7	+	5	36	29	9.0	7.8	3.1	2.4	-0.5	-1.0
	4	19/7	+	1	48	50	9.5	10.6	3.3	4.1	-3.0	-2.4
Ellef Ringnes,	1	20/7	0	3	26	32	6.7	8.0	0.8	2.8	-1.2	-0.8
Seismic Line	2	20/7	0	2	27	35	12.8	12.6	2.9	3.5	-2.1	-1.4
(IV-b)	3	20/7	+	3	29	34	11.2	15.1	3.3	4.0	-1.1	-1.0
Ellesmere,	1	26/7	2	5	45	45	8.3	9.8	5.4	4.1	-0.8	-1.3
Fosheim Pen-	2	26/7	+	5	42	44	6.1	6.6	3.9	3.2	-0.8	-0.8
insula	3	28/7	+	5	79	79	7.9	8.0	6.5	13.0	-1.5	-0.9
(V)	4	30/7	1	6	45	46	10.7	10.7	8.1	6.1	-0.7	-0.7
	5	31/7	3	3	53	55	12.3	9.5	6.5	6.5	-0.8	-0.8

* Live and dead plant material; + = < 1%; 1 = 1-2%; 2 = 2-5%; 3 = 5-10%; 4 = 10-20%; 5 = 20-50%; 6 = 50-100%.

temperatures and insolation were low, and warmer than controls when they were high. Because of a combination of shading and increased moisture, temperatures in deeply rutted tracks tended to be cooler than on drier, more resistant surfaces.

Because of their variability, individual surface readings showed no significant relationship to thaw depth, though those at 15 cm correlated highly (for disturbed surfaces in Table 11 r=.7013 and for undisturbed surfaces r=.926; r=.601 is significant at P=.99). At a single point in time, temperatures at 15 cm are therefore much more useful indicators of local energy regimes than are surface readings. The slightly lower correlation at depth for undisturbed surfaces illustrates a buffering against soil temperature fluctuations by intact plant cover. It may also reflect greater thermal conductivity in compacted and moister disturbed soils, and therefore a slightly closer coupling at depth to daily weather changes.

Although at individual sites there were significant differences in thaw depth and subsurface temperatures between disturbed and control surfaces, for the 14 sites in total there was no consistent or significant relationship.

The occurrence of thermokarst on disturbed arctic sites depends largely on ice content of subsurface layers. Ice conditions have been studied extensively in more southerly regions (Mackay 1966, 1970, and many others), but not as much is known about those in the Archipelago. Although pingoes have been reported on Prince Patrick Island, such features are generally rare. To the author's knowledge, coastal reg-

ression, formation of thaw lakes and similar conspicuous natural thermokarst phenomena indicating the presence of massive beds of ground ice have not been reported.

According to Mackay (1971) formation of large subsurface ice masses depends primarily on the presence of coarse grained sediments overlain by less permeable fine-grained layers as well as on occasional degradation and aggradation of permafrost with changes in climate or sea level. Both of these conditions seem less likely in the northern islands, the first because of the absence of major drainages similar to those of the Mackenzie Delta and the Alaskan North Slope, and the second because of the more extreme climate in the islands and the relative "permanence" of permafrost.

Under localized conditions, however, significant amounts of less massive lens and wedge ice no doubt exist. Visible thermokarst at sites on Melville (Appendix Fig. 5) and Devon Islands (Appendix Fig. 2) substantiate this. Polygonal patterning indicating the presence of ice wedges is a ubiquitous feature in meadows as well as in many better-drained upland sites. Most soil pits dug near the time of maximum thaw revealed supersaturated frozen material with up to 40% ice content by volume immediately below the active layer.

Though subsurface conditions have yet to be quantified, the scarceness of thermokarst following disturbance or under natural conditions is, in the opinion of the author, to a large degree dependant upon surface energy budgets rather than necessarily low permafrost ice contents (see pp. 24-28).

One characteristic of High Arctic soils which has not been dealt with extensively, and one which is important with regard to disturbance is that of a strong moisture gradient within many profiles. This has been dealt with primarily as a drainage phenomenon but rarely in a physical sense as a function of soil temperature. Water tends to move toward cold areas in a soil profile by a process of condensation (Taylor 1962). At the upper surface of the active layer temperatures were usually well above 5^{o} as opposed to 0^{o} or lower at the thaw interface (Table 11). The temperature gradient alone is probably to a large degree responsible for a corresponding moisture gradient from dry at the surface to wet at a depth of 10 cm or more during the summer months in most fine-grained polar desert soils.

As plants usually play a lesser role in surface energy budgets than in the Low Arctic, permafrost is not as sensitive to the revoval of vegetation alone. In many areas, however, though vegetation is sparse, disturbance of the surface can have harmful microenvironmental effects. A layer of relatively compact silt and clay comprising the active layer may lie on top of permanently frozen material with a much higher water (ice) content than the layer above (e.g. Profile 1). Disturbance of this overburden can result in thaw by an amount proportional to the amount of soil removed or compacted. When this occurs the remaining surface soil is left essentially floating on a dense but fluid mixture of clay and water several centimeters thick. On slopes this

layer can act as a lubricant for massive sliding. On level ground the moisture released by thaw eventually permeates the upper layers and softens previously dry, solid material.

Changes in soil moisture may be sufficient to slow natural revegetation, for the habitat may no support xerophytic species previously present. Species adapted to moister habitats may temporarily invade such areas, but the process has not been observed. It is probably quite slow because of the infrequency of seed production and seedling establishment.

SUMMARY

1) High Arctic soils are primarily Regosolic or Gleysolic mineral soils. Organic soils are relatively rare. During summer months moisture in fine-grained soils near the base of the active layer promotes soil instability, especially when compaction or removal of surface layers results in slightly increased thaw depth.

2) Sixty passes in a mesic sedge meadow community on Devon Island with a light tracked vehicle did not significantly disrupt plant cover or affect the thickness of the active layer.

3) Movement of heavier vehicles and other activities on High Arctic terrain can reduce plant cover 50 to 100%. In polar desert areas the overall effect is small. In protected sites where cover approaches 100%, disturbance has effects similar to those in the Low Arctic.

4) Removal of all vegetation from a mesic sedge meadow surface on Devon Island altered the surface energy budget. Albedo increased; longwave reradiation increased, and latent and sensible heat loss to the atmosphere increased. The net result was a relatively small increase in soil heat flux which corresponded to an increase in the thickness of the active layer of only 10 to 15%.

5) Thickness of the active layer was found to be 0 to 15% greater on disturbed High Arctic surfaces than on controls. The smallest increases were on sparsely vegetated xeric sites, and the greatest were in low-lying meadows with 100% plant cover. In very few instances, if any, was thaw increased as much as in Low Arctic tundras. It is thought that this decreased sensitivity of subsurface ice to disturbance is primarily a function of low air temperatures during the summer in addition to low permafrost temperatures.

6) Reinvasion on disturbed areas is relatively slow. Efficient seed or bulbil producers are most rapid reinvaders on mesic or dry sites. In meadows invasion by vascular plants is primarily lateral encroachment by rhizomes. There may be physiological limitations to the later mode of revegetation.

7) Growth rates of at least some species are limited by low nutrient levels in High Arctic soils. Plants in beach ridge and mesic sedge meadow habitats on Devon Island showed increased growth with addition of both nitrogen and phosphorus.

Potassium alone had no effect, probably because it is at relatively high levels in untreated soils. The three elements in combination appeared to have a greater than additive effect, perhaps because of mutual enhancement by nitrogen and phosphorus. Because of varying responses by different species, drastic plant community changes result from "natural" manuring, and would probably result from artificial fertilization as well.

8) Bi-weekly clipping of graminoids on mesic sedge meadow plots on Devon Island reduced above-ground dry matter yield by 20-30%. It is suspected that the depletion of overwintering carbohydrate reserves will result in greater yield reduction in subsequent years.

9) Spilled diesel fuel on beach ridge and mesic meadow communities on Devon reduced live vascular plant cover by as much as 50% one year following treatment. Lichens on the beach ridge appear not to have been affected.

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APPENDIX

The following descriptions cover the localities referred to in text and tables. Sites described are referred to by the numbers here.

I. Bathurst Island, Freeman's Cove (75° 07'N, 98° 01'W) July 12-14, 1970.

Topography is moderately hilly with smooth contours. The area is underlain by calcareous sandstone which is exposed on upland surfaces but does not crop out abruptly. Depressions are poorly drained and filled with unconsolidated fine sand and silt weathered from the parent material. In the immediate vicinity of the coast the surface has been modified by the action of sea ice during isostatic rebound following deglaciation. A single broad, sloping beach ridge has formed.

The well-drained rocky upland surfaces are vegetated by a discontinuous cover of mesophytic species (e.g. *Salix arctica*, *Dryas integrifolia*, *Saxifraga oppositifolia*, *Draba* spp., mosses and lichens). Undrained depressions and late snowbank areas at the bases of slopes have a more continuous cover of mosses, sedges, and grasses.

Disturbance by vehicle movement is minor on resistant, elevated surfaces. In some depressions where unconsolidated material has accumulated, but where better drainage has developed, plant cover is susceptible to damage during the first

2-3 weeks following thaw but is more resistant when the surface dries and hardens later in the season. Around pond margins where the soil is continuously wet, cover is easily broken by vehicle passage during most of the summer.

Site Descriptions:

1. A meadow at a pond margin. Moss cover was complete and vascular plant cover consisted of a single unidentified sedge species (20%). The soil sample taken (Table 3) was sandy mineral soil from immediately below the moss blanket.
2. A rocky beach slope approximately 10 m above present sea level. Vegetation was sparse (lichens and mosses alone, cover 1%). Soil samples were taken at 5 cm and 30 cm depth (Table 3).
3. A fox den site at the top of a stream bank. The site was depressional but well drained, and was on a relatively dry, unconsolidated, sandy substrate. See table 10 in text for plant cover by species. Increased nutrients and moisture retaining capacity from accumulation of organic material were probably responsible for the lush plant growth noted.

II. Cornwallis Island, Resolute Bay (74° 44'N, 95° 55'W), July, 1970 and 1971.

Relief is slightly greater than at sites on the western islands. Parent materials are shales, limestones and sandstones. Soil is predominantly coarse and rocky polar desert soil. There is very little continuous tundra vegetation.

Although many of the "polar desert" sites are probably truly xeric because of rapid drainage through coarse-grained substrates, many moister sites are sparsely vegetated as well. Limitations to plant production are probably due in part to moisture availability, but the exceptionally foggy and misty summer season (Cruickshank 1971) with subsequently low soil and surface boundary layer temperatures is likewise important. Low nutrient levels may also be involved.

On drier sites most common species are *Salix arctica*, *Dryas integrifolia*, *Saxifraga oppositifolia*, *Draba* spp., *Papaver radicatum*, *Cerasteum alpinum*, *Arenaria rubella*, *Puccinellia vaginata*, *Poa abbreviata*, mosses and lichens. In moister sites are *Arctagrostis latifolia*, *Alopecurus alpinus*, *Carex* spp., *Stellaria humifusa*, *Ranunculus* spp., *Saxifraga cernua*, and mosses.

Disturbance is extensive and of varying ages in the vicinity of the settlement and airstrip. Reinvasion by vascular plants and mosses is extremely slow, and none by lichens is evident. With the exception of *Dryas* and *Salix* almost all vascular species found on undisturbed surfaces occur as reinvaders at considerably lower densities on scraped areas. *Saxifraga oppositifolia* cushions are occasionally the only plants on some denuded sites; these from their size must have been established at least 20 years previously, nothing else having successfully invaded since. Crucifers (*Braya purpurascens* and *Draba* spp.) as elsewhere, appear to have a slight advantage in initial reinvasion, though they are far too sparse to be considered as playing a "competetive" role in

succession.

III. Devon Island, Truelove Lowland (75° 40'N, 84° 40'W), Aug., 1970 and 1971.

The lowland is the location of the Canadian IBP Tundra Biome Terrestrial Productivity study and is described in detail in reports by that group (e.g. Bliss 1972). It is a complex of elevated beach ridges and meadows surrounded on two sides by cliffs, and by sea on the northern and western perimeter. Parent materials are a mixture of glacially deposited Precambrian granitics and Paleozoic dolomite and calcareous sandstone. Soils have been described in some detail (Peters and Walker 1972) and vary from Gleysols or Gleyed Regosols in meadows to Brunisols on better drained, mature upland sites. Deep peat accumulations, which are generally rare in the High Arctic, occur in the area.

Meadow vegetation is primarily mosses, *Carex* spp., *Eriophorum triste*, *Juncus* spp., *Arctagrostis latifolia*, *Equisetum variegatum*, and a number of rarer grasses, sedges, and broadleafed species (Muc 1972). Beach ridges are vegetated by *Salix arctica*, *Dryas integrifolia*, *Carex nardina*, *Saxifraga oppositifolia*, mosses, lichens, and a variety of other mesophytic or xerophytic species in smaller numbers (Svoboda 1972). Granitic rock outcrops offer unique microhabitats where reflected insolation, warm soils, pockets of nutrient accumulation and protection from wind enable a broad variety of species to grow, sometimes quite vigorously.

Most of the disturbance in the area is from scientific activities during the use of Arctic Institute facilities over the past 10-12 years. Vehicle tracks were created mainly by two Massey-Ferguson wheeled tractors with chain link, cleated assistance on the rear wheels, and by a "Ranger" rubber tracked vehicle. Older disturbance is in a slow process of natural recovery, though in one meadow and rock outcrop area, active erosion and thermokarst may still be in progress following disturbance 5-10 years old (Appendix Fig. 2).

Site Descriptions:

1. A ten year-old vehicle trail at an old Arctic Institute campsite near the north end of the lowland (see map, Appendix Fig. 1). Plant cover is described in Table 10.
2. A vehicle track in a meadow near site 1. The trail is on a slight slope, and revegetation has been hindered by erosion and the formation of ruts up to 20 cm deep. Although the meadow is peaty (20-30 cm), mineral soil is exposed along much of the inclined portion of the track. Plant cover is described in Table 10.
3. A muskox trail on a talus slope at the northern end of the lowland, along a route which connects the area with the Sparbo-Hardy Lowland to the north. Dung has accumulated along the path, while the adjacent substrate consists entirely of granite cobbles with no fine materials. Plants along the trail in the

Appendix Figure 1. Map of the Truelove Lowland, Devon Island showing the location of manipulation experiments and study sites (1-5).

a = Meadow fertilization plots
b = Meadow controlled vehicle passage
c = Simulated blading, meadow oil spills
d = Beach ridge fertilization plots, oil spills
e = Clipping experiment

organic substrate are _Heirochloe alpina_, _Saxifraga cernua_, _S. nivalis_, _S. caespitosa_, and _Cerasteum alpinum_. A sample of the soil was taken for nutrient analyses (Table 3).

4. A muskox carcass dated by growth of Salix arctica as 13-20 years old. The site is on a well-drained beach ridge substrate near a rock outcrop about 3/4 km from the mouth of the Truelove River (Appendix Fig. 1). Vegetation is described in Table 10.

5. A muskox carcass dated as 3 years old by Eskimo hunters from Grise Fiord. The site is in a mesic depression in a rock outcrop near the icebreaker supply landing (Appendix Fig. 1). Vegetation is described in Table 10.

IV-a. Ellef Ringnes, Hoodoo Dome (appr. 78° 15'N, 100° 00'W). July 17-19, 1971.

Relief is low with hills rarely over 20 m in height. Parent materials are weakly consolidated sediments weathering _in situ_. Mass wastage is primarily by wind erosion, amorphous solifluction, and creep which result in smoothly contoured surfaces. Drainage is well developed with few permanently wet sites. Water erosion is mostly from rapid runoff during snowmelt in June. Gullies are up to 5 m deep with typically abrupt and rounded banks, the result of slow downslope movement of soil by creep in combination with periodic more rapid erosion by running water.

Vegetation is a relatively homogeneous and discontinuous vascular plant, moss, and lichen cover. In moister depressions are Alopecurus alpinus, Luzula confusa, Stellaria longipes, Phippsia algida, Cardamine bellidifolia, Saxifraga rivularis, Potentilla hyparctica, Ranunculus sabenei, mosses and lichens with total cover approaching 80%. On elevated or dry sites vegetation is sparser, consisting primarily of Papaver radicatum, Draba spp., Puccinellia andersonii, P. phryganoides, and lichens with cover sometimes less than 1%. Streambeds are sandy and devoid of vegetation.

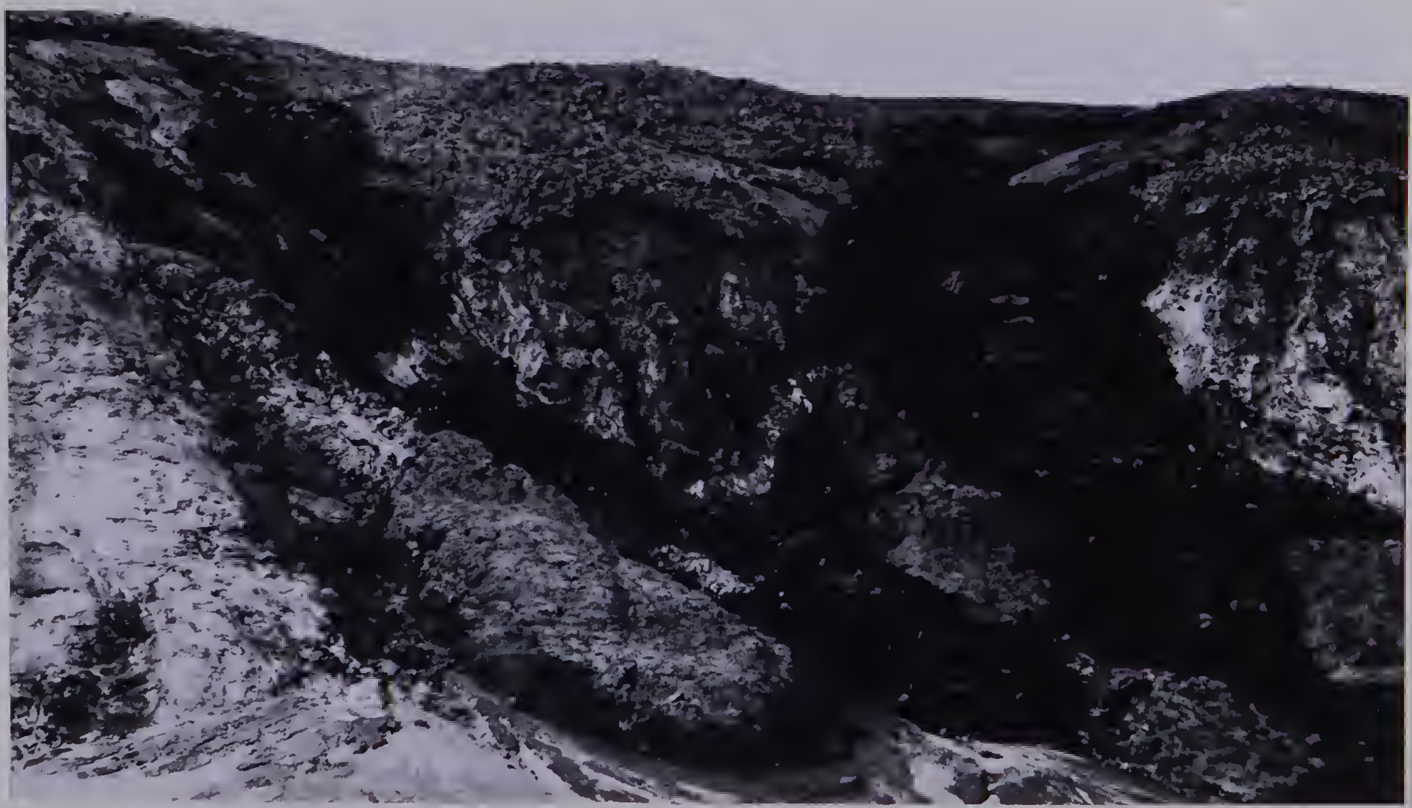
A sharp moisture gradient in soil profiles and high water content in the upper layer of permafrost (20-50% by volume) result in some soil instability and susceptibility to softening following disturbance. Mudslides are a natural occurrence on streambanks (Appendix Fig. 3), and slopes are therefore especially sensitive. Although vascular plant cover is sparse, thaw depth is significantly affected by light scraping. As lichens predominate on many surfaces, they may play a significant role in surface energy budgets.

Site Descriptions:

1. A lightly bladed winter airstrip on level ground. Undisturbed vegetation was a 50% cover of lichens, mosses, and vascular plants. The mosses were mostly dead and eroded, leaving the rhizomes as a thin, dry peatlike layer. Vascular plants were primarily species listed for moister sites (above). Of existing plant cover, 50-100% had been removed (1970-71).

Appendix Figure 2. Slump and erosion resulting from vehicle passage in a peaty meadow on Devon Island.

Appendix Figure 3. A naturally occurring mudslide on the bank of a stream near Hoodoo Dome, Ellef Ringnes Island. The photograph spans a distance of approximately 13 m.



Sites a and b were areas where approximately 5 and 30% respectively of original cover remained.

2. A vehicle trail on a slope vegetated similarly to Site 1 but with a sparser cover of vascular plant species more typical of dry sites.

3. A vehicle trail on the southeast facing slope of a streambank. Plant cover was primarily Luzula confusa on the control surface. Soil was sandy silt.

4. The northwest facing bank of the same stream (opposite Site 3). Soil was silty, dry, hard, windblown, saline and sparsely vegetated, the only species present being Puccinellia andersonii and P. phryganoides. It is thought that the site characteristics were due more to hydrology than to aspect, for the immediate vicinity was an area of groundwater discharge and salinization.

IV-b. Ellef Ringnes, Seismic Line (78° 18'N, 101° 28'W), July 20, 1971.

Relief is somewhat greater than at the above location Hills up to 80 m high x 2 km broad). but parent materials and dominant geomorphic processes are similar. With greater variation in drainage and aspect there is less widespread homogeneity of vegetation, though the sites discussed here were quite similar in spite of topographic differences. Disturbance is from movement of a seismic crew and equipment during early spring operations immediatly following snowmelt.

Site Descriptions:

1. A hillside on a N.W. facing slope about 300 m from the crest of a hill (Site 2). Soil is a silty loam, dry and cracked at the surface and increasingly moist with depth. Plant cover on the undisturbed surface is approximately 8% consisting mainly of _Alopecurus alpinus_, _Papaver radicatum_, _Draba_ spp., _Saxifraga cernua_, _Ranunculus sabenei_, _Cerasteum alpinum_, _Phippsia algida_, mosses, and lichens. Vegetation was entirely gone from the trail, and all soil thawed at the time of disturbance had been removed (15-20 cm).

2. Hillcrest. The site is drier and more sparsely vegetated than Site 1 and has the same species present but with a cover of only 2-3%, primarily _Alopecurus_. There are more coarse fragments in the soil and a discontinuous gravel pavement makes up approxi- 10% of the surface. Salt crusts were seen. Disturbance was as on Site 1.

3. Near the base of the hill. Within the sample area characteristics of substrate and vegetation were quite similar to Site 1 with slightly more moisture evident and with more conspicuous flowering of _Ranunculus_. In an adjacent depressional area through which the trail passed were more mosses (cover up to 60%), and in addition to the above species, _Saxifraga nivalis_, _S. caespitosa_, _S. rivularis_,

S. flagillaris, and *Stellaria longipes*. Disturbance in this moist depression was nil as snow had apparently not yet melted at the time the vehicles passed.

V. Ellesmere Island, Fosheim Peninsula, July 24-Aug. 1, 1971.

A 120 km trip was made on foot from a Panarctic rig site (79° 37'N, 84° 44'W), north along Eureka Sound to Slidre Fiord, east 20 km past Romulus Lake, and west along the north side of Slidre Fiord to Eureka (79° 58'N, 85° 47'W). Vehicle tracks and other disturbances were investigated along this route.

The region is one of the more environmentally diverse in the Archipelago. Maritime influence is weak as the fiords surrounding the peninsula are narrow. Climate is primarily under the influence of the mountainous landmasses of Axel Heiberg and Ellesmere Islands. Parent materials are sedimentary or glacial in origin, and are usually well drained. Soils exhibit the effect of a warmer summer climate than in areas such as Cornwallis and Ellef Ringnes Islands. Thaw depths of up to 1 m and surface soil temperatures up to 20° were measured here. In the vicinity south of Slidre Fiord, the Slidre River and Romulus Lake (79° 49' N, 85° 07'W) salt crusts form on many surfaces; runoff is brackish or strongly salty, and vegetation is relatively sparse.

Lowland sites have polar desert or semi polar desert vegetation except near protected late snowbanks or where a continuous source of fresh water is available. *Salix arctica*

is a widespread dominant, and _Dryas integrifolia_ is important in more restricted localities. Also important are _Puccinellia angustata_, _Deschampsia brevifolia_, _Agrostis latiglume_, _Alopecurus alpinus_, _Cerasteum alpinum_, _C. beeringianum_, _Saxifraga tricuspidata_, _Melandrium triflorum_, _Potentilla rubricaulis_, and _Oxyria digyna_. In moister meadows are _Eriophorum triste_, _Carex stans_, _Polygonum viviparum_, _Arctagrostis latifolia_, _Alopecurus alpinus_, _Saxifraga hirculus_, and mosses.

Most of the disturbance observed was along a trail used by heavy "Nodwell" tracked vehicles between the Panarctic rig and Eureka. After approximately 20 passes the depth of the depression varied from 0 to 30 cm, with almost all vegetation having been removed from an estimated 20% of the trail and with gradations from 0 to 100% removal from the remainder.

Site Descriptions:

1. Between the rig site and Fluker Pt. (appr. 79° 39'N 84° 40'W); a mesic to dry site with approximately 50% cover, primarily _Salix arctica_ plus all of the species listed for dry sites above). Soil is a silty loam. The undisturbed surface is a complex of 1 m diameter polygonal blocks separated by cracks up to 20 cm deep. Through frost action and seasonal drying, soil appears to move towards the edges of these, gradually drawing accumulated litter downward into the cracks. The cracks appear to be the most favorable habitat for seedling establishment

and plant growth, the centers of these polygons or boils being exposed and dry during most of the growing season.

2. Similar to Site 1, about 25 km north on the same trail. Undisturbed cover is primarily Dryas integrifolia, Salix arctica, Carex misandra, Polygonum viviparum, and mosses with total cover approximately 50%.

3. A mesic meadow on a north-facing slope about 3 km south of the mouth of the Slidre River. The site is probably watered by winter snow accumulation in the lee of the ridge directly to the north. Vegetation consists of meadow species as described above and Dryas integrifolia (cover $<$ 1%).

4. Eureka airstrip. The area is an uplifted surface where the loamy substrate had been scraped upwards for use as airstrip landfill. Vegetation is described in Table 10. Recovery is almost complete, though Salix arctica has to a large degree been replaced by grasses. The site is in much the same condition as it was 10 years previously according to Beschel (1963b).

VI. King Christian Island (77° 47'N, 101° 00'W), Aug. 2, 1971.

The island was visited only briefly on one day. Topography, substrate, and vegetation are similar to those on

nearby Ellef Ringnes, though relief is lower, and the maritime influence may provide slightly moister, cooler conditions for plant growth. Cover consists mainly of mosses and lichens with Saxifraga oppositifolia, S. nivalis, S. cernua, Stellaria longipes, Cerasteum alpinum, Alopecurus alpinus, Luzula confusa, and Puccinellia phryganoides as the vascular species observed. Maximum cover was about 50%.

Disturbance is much like that elsewhere, consisting primarily of vehicle tracks or lightly scraped airstrip surfaces. No thermokarst was evident, and traces of a 1970 gas blowout were not seen.

VII. MacKenzie King Island, Cape Norem (77° 28'N, 110° 30'W), July 19-22, 1970.

The island is low-lying and sparsely vegetated. At this location on the southeast coast, the land surface is a gently inclined plain sloping towards the sea. The substrate is a Quaternary deposit of silt and sand exposed by isostatic uplift following deglaciation. Apparently the slope is so gradual that offshore water was too shallow for sea ice to have affected formation of beach ridges. The plain is shallowly cut by small watercourses active during spring snowmelt. Soil is saline and hard. Vegetation consists of widely separated tussocks of non-woody perennials such as Puccinellia brugemanii, Alopecurus alpinus, Papaver radicatum, Stellaria humifusa, Draba spp., Cochlearia officinalis, and Ranunculus sp.

VIII. Melville Island, Sherard Bay (76° 05'N, 108° 25'W), July 23-25, 1970.

The area is part of a complex of poorly or partially drained lowlands along the coast of the Sabine Peninsula. The substrate in the immediate vicinity is moist, unconsolidated sand. Vegetation on level sites is lush meadow of grasses and sedges (*Arctagrostis latifolia*, *Poa alpigena*, *Deschampsia* sp., *Dupontia fisheri*, and *Carex* spp.) in a 4-5 cm layer of moss. More mesophytic species grow in the elevated margins of low-center polygons (*Salix arctica*, *Ranunculus sabenei*, *Papaver radicatum*, *Saxifraga nivalis*, *Potentilla hyparctica*). On slopes above streambeds a more diverse mesophytic flora is found (*Dryas integrifolia*, *Draba* spp., *Oxyria digyna*, *Luzula confusa*, *Saxifraga* spp., *Cochlearia officinalis*, *Braya purpurascens*, *Papaver radicatum*, *Stellaria longipes*, *Cerasteum alpinum*, and others).

Here, as in most highly vegetated High Arctic areas, the thin peat layer (4-5 cm) on raw mineral soil is especially sensitive to disturbance. Plant cover and virtually all of the supporting organic substrate can be removed by a single pass of even a "low impact" vehicle (Appendix Fig. 4). Recovery was not apparent in tracks investigated, though it is possible that damage was newer than the three years reported by oil-camp personnel. Evidence here and elsewhere indicates that recovery on entirely bared areas will be slow. At the margins of streams, some slumping from the melting of underground ice was evident (Appendix Fig. 5).

Site Descriptions

1. A meadow site as described above. Soil sample was sand taken from directly below the 5 cm moss layer (Table 3).
2. Similar to site 1, vehicle tracks with vegetation removed, possibly as old as three years.
3. Dry, better drained site at meadow margin, scraped very lightly for light aircraft strip 2 years previously such that some underground rhizomes, etc. were probably intact following disturbance. Vegetation is described in Table 10.

Appendix Figure 4. Exposure of mineral soil below a 5 cm moss layer resulting from vehicle passage, Sherard Bay, Melville Island.

Appendix Figure 5. Erosion and slump resulting from surface disturbance on a stream bank, Sherard Bay, Melville Island.